

# Quadrocopter Control Design and Flight Operation

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**A limiting factor in control system design and analysis for spacecraft is the inability to physically test new algorithms quickly and cheaply. Test flights of space vehicles are costly and take much preparation. As such, EV41 recently acquired a small research quadrocopter that has the ability to be a test bed for new control systems. This project focused on learning how to operate, fly, and maintain the quadrocopter, as well as developing and testing protocols for its use. In parallel to this effort, developing a model in Simulink facilitated the design and analysis of simple control systems for the quadrocopter. Software provided by the manufacturer enabled testing of the Simulink control system on the vehicle.**

## Nomenclature

$x$	=	state vector (n x 1 vector)
$v$	=	input vector (m x 1 vector)
$f(x)$	=	nonlinear function of the system states (n x 1 vector)
$G(x)$	=	nonlinear function of the system states (m x n matrix)
$\phi$	=	bank (roll) angle (rad)
$\theta$	=	pitch angle (rad)
$\psi$	=	azimuth (yaw) angle (rad)
$K_p$	=	proportional gain
$K_d$	=	derivative gain
$K_i$	=	integral gain

## I. Introduction

For spacecraft design, an important and often complex component is the control system, which keeps the vehicle on track and adjusts for unforeseen variations. However, spacecraft are expensive to test and take significant time to set up. With the continuing advances in control theory, it is helpful to be able to test the new algorithms, and while computer software has good simulation capabilities, the lessons learned from real-world testing can be invaluable.

Recently, small air vehicles have gained great capabilities and have become suitable for research purposes. One example is the line of quadrocopters from Ascending Technologies (AscTec), which provide a small, lightweight, and relatively inexpensive platform to test control programs on. A quadrocopter is an air vehicle that is lifted and controlled by four rotors. With the onboard microprocessors, they are powerful machines and can be used to quickly and easily perform tests.

The control systems design and analysis branch (EV41) at Marshall Space Flight Center (MSFC) recently purchased an AscTec Hummingbird quadrocopter. The main purpose of this project was to set up the system once it arrived. This included establishing protocol and areas for its use and learning how the hardware and software operated. In conjunction with this task, this project also designed a model and simple controller in Simulink.

## II. Quadrocopter Setup

### A. AscTec Hummingbird

The quadrocopter is an AscTec Hummingbird. Table 1 lists many of the technical details of the quadrocopter<sup>1</sup>. The frame is made out of balsa wood and carbon fiber<sup>2</sup>, making it strong and lightweight. For sensors, the copter has a pressure sensor, an acceleration sensor, and three gyroscopes (one for each axis). It also has a three-axis compass and a GPS unit. All the sensors besides the GPS compose the Inertial Measurement Unit (IMU). The AutoPilot circuit board has two microcontrollers—a low level processor (LLP) and a high level

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processor (HLP). The LLP compiles the IMU data, sends commands to the motor controllers, and also has the basic attitude controller that comes with the quadcopter. The HLP controls the GPS, but is mostly free as a space for the user-defined programs.

**Table 1. Technical Details of the Quadcopter.<sup>1</sup>**

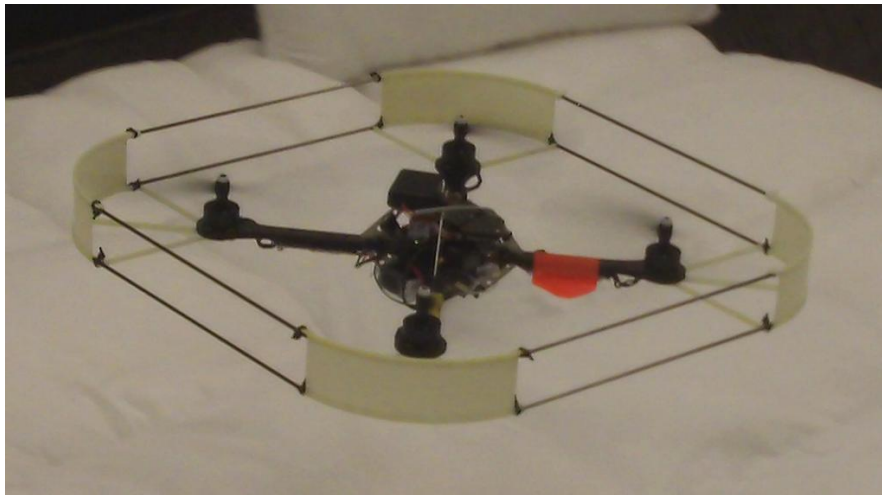
Model	AscTec Hummingbird with AutoPilot
Manufacturer	Ascending Technologies GmbH
Battery	2100 mAh LiPo
Takeoff weight	480 g
Distance between motors	34 cm
Propeller	8" flexible standard propellers
Motors	AscTec X-BL 52s with X-BLDC controllers
Radio controller	Futaba FFAST 2.4 GHz
Telemetry system	Xbee 2.4 GHz

The quadcopter is controlled solely by motor speeds. As shown in Fig. 1, the front and rear propellers spin clockwise and the left and right motors spin counterclockwise. In this way, all three axes can be controlled through changing the rotation speeds. Roll is controlled by manipulating the speeds of the right and left motors; pitch is similarly controlled by the front and rear motors. Yaw is controlled by a combination of all four motors by speeding up the motors spinning in one direction and slowing the ones spinning the other way. This turns the quadcopter by causing a change in angular momentum, but it does not affect the pitch and roll axes.



**Figure 1. AscTec Hummingbird Quadcopter.<sup>1</sup>** *This image is of a standard Hummingbird Quadcopter. The arrows show the rotation direction of the propellers, with the front and rear spinning clockwise and the left and right spinning counter clockwise.*

For safety, the quadcopter was ordered with propeller protection, which connects to the arms of the quadcopter and consists of lightweight corner pieces connected by carbon tubes.



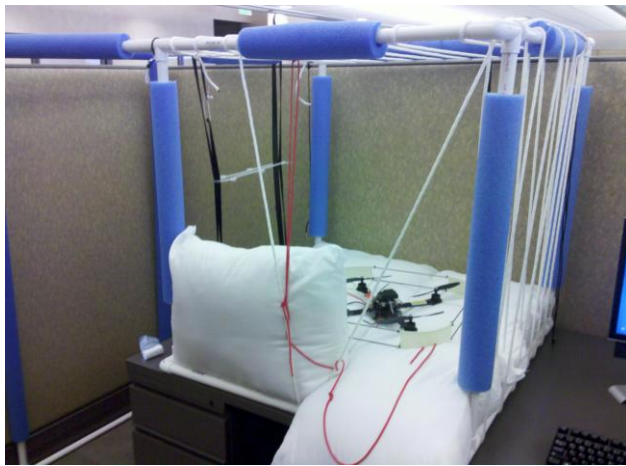
**Figure 2. Quadcopter in Flight.** *This image is of the vehicle with the propeller protection on, during indoor flight.*

## B. Indoor Flight Environment

The quadcopter will be mainly used in an indoor environment. To protect people, property, and the quadcopter, it was decided that there should be a caged area that is designated as controlled flying space. Initially, there were two planned spaces, one in the cubicle and one in a spare file room. Both were built of PVC pipe, with netting and padding.

The smaller space took up a corner of the cubicle and was built to be partially on the desk with the rest of the area extending the full distance to the floor. The idea of this space was to be for quick testing of sensor data readings. The first flights of the quadcopter were in this space, but it was quickly determined that the quadcopter was noisy enough to be a bother in the office and this space was dismantled.

The larger space is a 10'x10'x8.5' cube in a spare file room. This area is made of 1.25" PVC pipe, with wood supports on the corners and foam padding on the structure. Baseball netting covers the whole structure, stretched taught to be able to catch and contain the quadcopter; the floor is covered with pillows, which were the cheapest and softest material to act as padding. A great feature of the quadcopter is the soft propellers, as they do not cut through the netting or pillows when they make contact. When impacting the netting, the propellers become caught, stopping the quadcopter. The cage was designed such that it can be dismantled and moved if necessary.



**Figure 3. Small Flying Area.** This image shows the quadcopter inside the small flying area, before it was dismantled.



**Figure 4. Quadcopter Cage.** This image shows the completed large flying area, with the pillows and netting.



**Figure 5. The Effectiveness of the Cage.** After hitting the net, the quadcopter is stuck, effectively stopping it.

### C. Mode Testing

The quadcopter comes with three different modes of operation: manual, height control, and GPS. Height control and GPS are intended for outdoor use, so the industrial safety department cleared the quadcopter to fly in an outdoor location, on the softball field at MSFC. The grass there was short and soft, making it a good location. While outdoors, all modes were tested, as well as maneuvering capability, full speed, and range.

#### 1. Manual Control

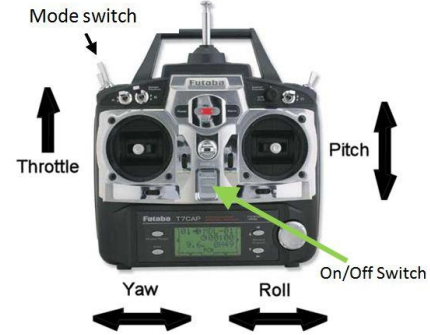
The majority of time was spent in this mode, in which the pilot controls all aspects of the quadcopter through the controller and it flies much like a normal RC aircraft. For safety reasons, a pilot must learn to fly in manually before using any of the other modes.

#### 2. Height Control

AscTec recommends that this mode is only used outside. In this mode, the throttle commands an ascend/descend rate instead of thrust, and when the stick is centered, the quadcopter will stay at a constant height.

#### 3. GPS Mode

This mode can only be used outside, as the GPS unit needs a clear view of the sky to work. Height control is enabled, the system uses the GPS to hold position, and roll/pitch/yaw maneuvers are speed controlled to 2 m/s. The user can send waypoint commands from the computer to the quadcopter. By sending a list of points to visit (waypoints), a path is created for the quadcopter to follow.



**Figure 6. Radio Controller<sup>2</sup>.** Using the Futaba 7-channel transmitter, the quadcopter can be controlled in all three axes, with throttle and mode control as well.

## III. Control Design

A parallel part of this project was to do control work with a computer model of the quadcopter. Control design seeks to make a system respond as precisely as possible to a given input, regardless of dynamics or disturbances. A control system uses sensors to measure the state of the plant (the process being controlled), determines the difference between the measured and desired values, and adjusts the plant accordingly with actuators<sup>3</sup>. In this case, the plant is the quadcopter and the actuators are the motors and propellers.

### A. Quadcopter Model

Before any control design can be done in simulation, the plant must be modeled. A common form of modeling a plant is through a state-space model, which takes the differential equations defining the system and puts them in a matrix format that can be used to better manipulate the system<sup>4</sup>. State-space models are traditionally represented as  $\dot{x} = Ax + Bu$  and  $y = Cx + Du$  (Ref. 4), but this representation is only applicable to linear systems. When a plant is non-linear the representation changes to  $\dot{x} = f(x) + G(x) \cdot v$  (Ref. 1). Below is the non-linear state-space representation of the quadcopter plant<sup>1</sup>. In this model,  $x = (\phi \ \dot{\phi} \ \theta \ \dot{\theta} \ \psi \ \dot{\psi})^T$ . A more thorough explanation and derivation of this model can be found in Ref 1. The control systems were all formed and tested around a Simulink<sup>5</sup> version of this model.

$$\begin{pmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \\ \dot{x}_5 \\ \dot{x}_6 \end{pmatrix} = \begin{pmatrix} x_2 \\ x_2 x_4 \tan x_3 + \frac{x_4 x_6}{\cos x_3} \\ x_4 \\ -x_2 x_6 \cos x_3 \\ x_6 \\ x_2 x_4 \frac{1}{\cos x_3} + x_4 x_6 \tan x_3 \end{pmatrix} + \begin{bmatrix} 0 & 0 & 0 \\ 1 & \sin x_1 \tan x_3 & \cos x_1 \tan x_3 \\ 0 & 0 & 0 \\ 0 & \cos x_1 & -\sin x_1 \\ 0 & 0 & 0 \\ 0 & \frac{\sin x_1}{\cos x_3} & \frac{\cos x_1}{\cos x_3} \end{bmatrix} \cdot \begin{pmatrix} v_1 \\ v_2 \\ v_3 \end{pmatrix} \quad y = \begin{pmatrix} y_1 \\ y_2 \\ y_3 \end{pmatrix} = \begin{pmatrix} x_1 \\ x_3 \\ x_5 \end{pmatrix} = \begin{pmatrix} \Phi \\ \Theta \\ \Psi \end{pmatrix} \quad (1)$$



The state-space model represented by Eqs. (1) were formulated into the Simulink model in Fig. 7. In the following models, R2011a edition of Matlab/Simulink was used. Figure 8 is the upper level of the Simulink program in which the control programs were run. The model in Fig. 7 is the contents of the Quad Plant block; the control design was done in the Attitude Control block, and the contents of the block for each control system are found in the following section. A constant command was fed into the system and the data was output into the Matlab workspace for analysis.

## B. PID Control

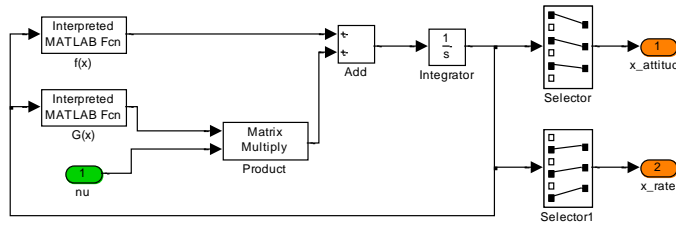
A common form of control system uses proportional (P), integral (I), and derivative (D) components. The proportional component consists of the difference between the commanded and measured values (the error). The integral component is the integral of the error, and the derivative component is the rate. There are four variations of this, proportional only (P), proportional-derivative (PD), proportional-integral (PI), and proportional-integral-derivative (PID). Each component has a gain associated with it ( $K_p$ ,  $K_i$ ,  $K_d$ ). By adjusting the gains of each component, the system response can be tuned.

Controllers are often tested by inputting a step function and analyzing the results. A step function is 0 for time less than 0 and some value for time greater than 0. In the following graphs, a step input of 10 degrees was used. There are four major characteristics of closed loop step response that are used as specifications to tune a system, all related to the steady-state, which is the value the system settles to. Rise time is the time it takes for the output to reach 90% of the desired value; overshoot is how much the peak is above the steady-state; settling time is the time it takes to converge to steady-state; and the steady-state error is the difference between steady-state and the desired value<sup>6</sup>. For this controller, the goals were to have a rise time of less than 0.5 s, an overshoot of less than 10%, a settling time of less than 1 second, and a steady-state error of less than 1 degree. These specifications were chosen because they are reasonable expectations for the performance of the quadcopter. Each gain has a specific effect on each of these characteristics, summarized in Table 2, so tuning a system is about balancing the effects. When tuning any kind of PID loop, the first gain to start with is the  $K_p$  gain, using it to decrease the rise time to within specifications. The next step is to use  $K_d$  to reduce the overshoot and settling time, but this will increase rise time, so it is a process of increasing each gain in increments to see the effects. The last step is to tune  $K_i$  to eliminate -state error.

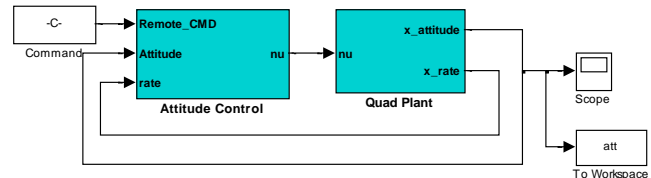
**Table 2. Effects of PID gains on Response Characteristics<sup>6</sup>**

	Rise time	Overshoot	Settling time	Steady-state error
$K_p$	Decrease	Increase	Small Change	Decrease
$K_d$	Small Change	Decrease	Decrease	Small Change
$K_i$	Decrease	Increase	Increase	Eliminate

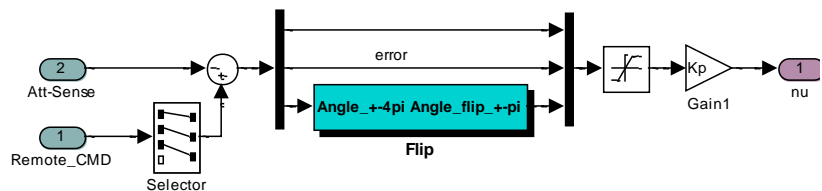
Figure 9 shows the attitude control block of a proportional controller. There is no rate input as seen in Fig. 8, and the thrust command (the 4<sup>th</sup> value of the given command vector) is not used in this model. The block Flip is from the Simulink software that was purchased with the quadcopter<sup>7</sup> and accounts for the full-circle nature of the yaw axis.



**Figure 7. Quadcopter plant model.** Using Eqs. (1), this Simulink diagram was created as a plant model for control design.



**Figure 8. Quadcopter Control System.** The control design is done in the attitude control block, based on the plant's response to a given command.

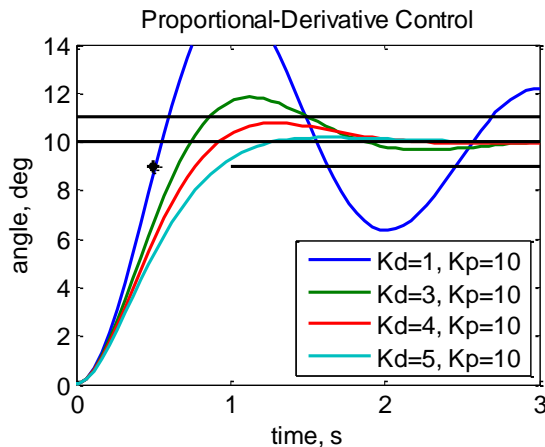


**Figure 9. Proportional Control Loop.** This is the attitude block for a simple proportional controller.

Figure 10 is the output of simulating the model with the control loop in Fig. 9, using varying values of  $K_p$ . Only the  $\phi$  (roll) axis was used for the purpose of testing the controllers. All the following PID testing graphs use the same settings unless otherwise noted. The black marks on the graph indicate the command input of 10 degrees and the tuning goals. The mark at (0.5,9) indicates the rise time goal, the middle line indicates the commanded angle, and the lines above and below mark the overshoot and steady-state parameters, respectively. When  $K_p$  equals 10, the model meets the rise time goal.

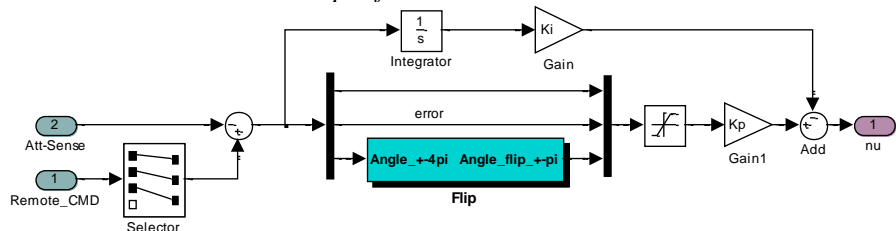
The next step in control design is to add a derivative, or rate, component to the control system. Figure 11 shows the attitude control with PD design. The attitude loop block is nearly identical to Fig. 3, and the rate feedback is multiplied by  $K_d$  and subtracted from the result of the proportional component.

$K_p=10$  produced the desired rise time, so the PD model ran with  $K_p=10$  and varying  $K_d$  values, as seen in Fig. 12.  $K_d=4$  brings the model within the desired overshoot limit, but increases the rise time, so  $K_p$  must be increased to compensate. Figure 13 shows the model with various values of  $K_p$  and  $K_d$ , with  $K_p=25$  and  $K_d=6$  bringing the model into accordance with the desired performance for both rise time and overshoot.

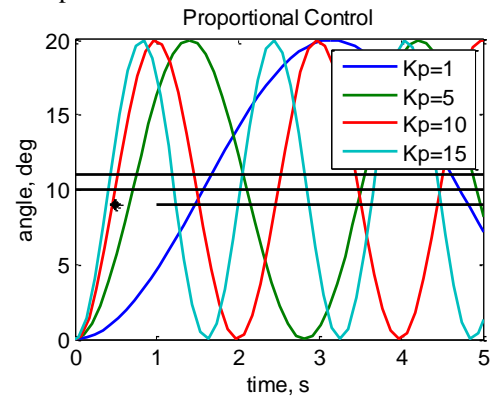


**Figure 12. Proportional-Derivative Control.** A simulation of the model with a PD controller, with  $K_p=10$  as found above.

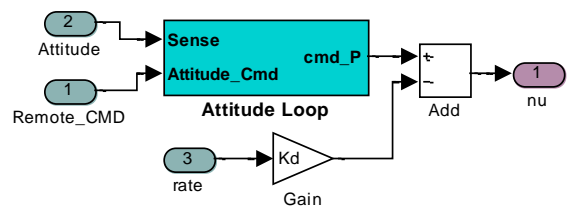
Proportional Integral control is also a common control system design; Fig. 14 shows a PI attitude control design. There is no rate component; instead, the error is integrated and multiplied by  $K_i$  and then subtracted from the proportional control component.



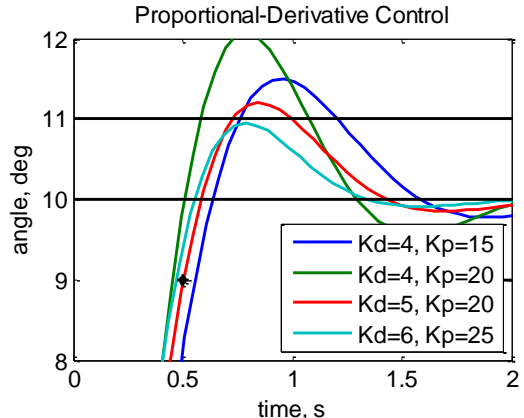
**Figure 14. Proportional-Integral Control Loop.** This is the contents of the attitude control block for a PI controller.



**Figure 10. Proportional Control.** A simulation of the model with just a proportional controller, with varying values of  $K_p$ .



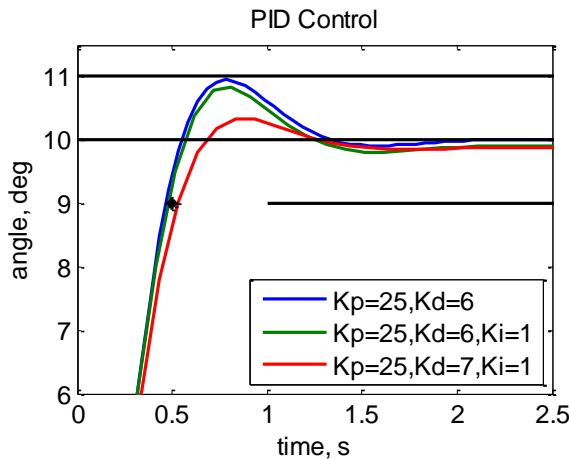
**Figure 11. Proportional-Derivative Control Loop.** This is the attitude control block for a PD controller, with a P controller in the attitude loop block and a rate component outside of it.



**Figure 13. Refined PD control.** Simulation of the model with varying  $K_p$  and  $K_d$  values, with  $K_d=6$  and  $K_p=25$  fitting the overshoot and rise time specifications.

As seen in Fig. 15, simulating the model with a PI controller was an ineffective control solution. The integral component did not solve the oscillations in the system. Low  $K_i$  values decreased the oscillations, but increasing the value led to integrator windup, resulting in a drop to negative infinity. Changing the  $K_p$  value with the same  $K_i$  value also did not have a desirable effect.

Despite the results of the PI controller, for the sake of completeness, a PID controller was also tested on the system.

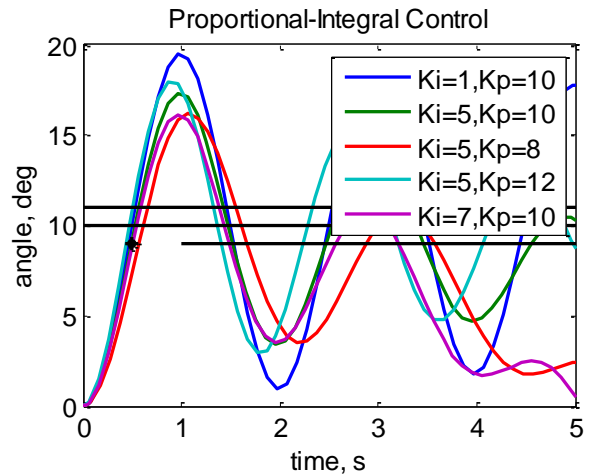


**Figure 16. PID Control.** Simulation of the model with proportional, integral, and derivative control components.

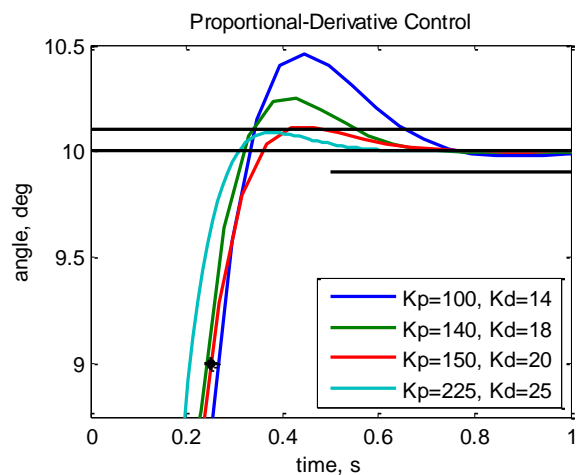
Figure 16 compares PD controller with  $K_d=6$  and  $K_p=25$  with similar PID controllers. The PID controllers reduce the overshoot slightly, but they also induce a steady-state error, which is not a problem with the PD controller, so a PID controller is not necessary. However, the  $K_d=6$  and  $K_p=25$  controller meets only three of the design specifications, as the settling time is greater than 1. It is also possible to improve the performance on the other specifications, so new specifications were selected.

As using higher gains for  $K_p$  and  $K_d$  leads to better a better system response, new parameters were selected and gains tested to fit the new specifications, which were rise time less than 0.25 s, overshoot less than 1%, settling time less than 1 s and no steady-state error. Figure 17 shows a few comparisons for these parameters.  $K_p=225$  and  $K_d=25$  fulfilled these specifications. It is worth noting that these gains happen to be close to the gains used in part of the first control system in Ref. 1, but are not exact due to the complexity of the system used in that work.

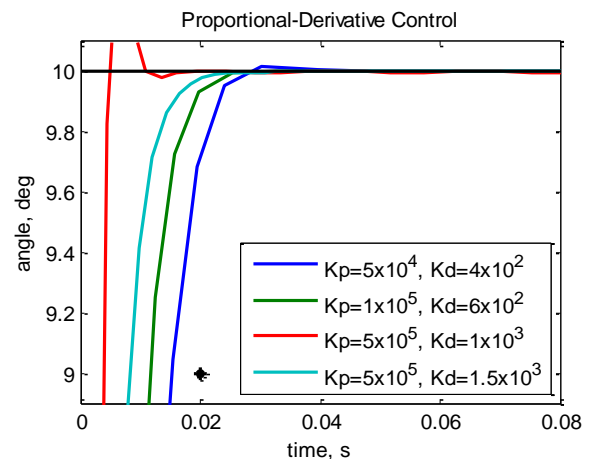
Next, even higher gains were tested. The results were that system performance could be brought to less than 0.02 s rise time, no overshoot, no steady-state error and settling time less than 0.04 s. However, while the gains tested in these simulations produced good performance, such large gains compromise robustness and may be limited by the fixed-point nature of the quadcopter microprocessors. Fixed-point numbers have less precision and a limited range of values as compared to some of the other common number types, such as single and double.



**Figure 15. Proportional-Integral Control.** Simulation of the model with varying  $K_p$  and  $K_i$  values.



**Figure 17. Further PD Testing.** This figure shows using higher gains to further refine the system response.



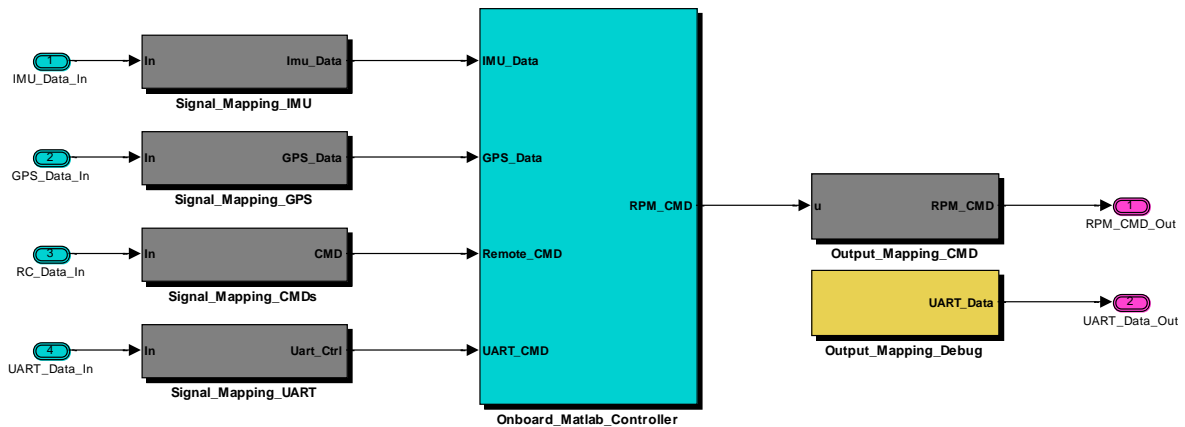
**Figure 18. High Gain Testing.** These simulations were run to test very large gains.

## IV. Flight Operation

The remaining part of this project was to combine the hardware and software. One of the powerful features of the AscTec Hummingbird is the ability to have user-loaded code on the HLP. In the long run, the main purpose of the quadcopter is as a test bed for custom code, so it was important to set up that part of the system. This involved installing and learning software and model from the manufacturer, and receiving data back from the quadcopter.

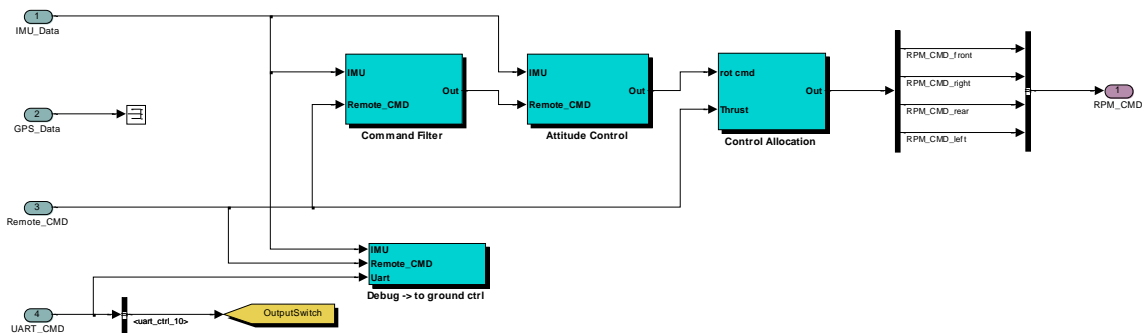
### A. AscTec Model

The quadcopter was purchased with a Simulink interface software package. This AscTec SDK<sup>7</sup> (Software Development Kit) included a Simulink model that, when converted to C code, is loaded onto the microprocessor using Eclipse software. The SDK also included a model to receive data back from the quadcopter, as well as many supporting files.



**Figure 19. Simulink Quadcopter Framework<sup>7</sup>.** This Simulink block diagram is the top level structure of the Simulink Quadcopter Framework that was purchased with the quadcopter.

The model shown in Fig. 19 gives an overview of the code framework that runs on the quadcopter. This model was designed for the R2010b edition of Matlab and was mainly run in that version, but work has been initiated to convert it to R2011b. Data from the IMU, GPS, RC controller, and UART (Universal Asynchronous Receiver Transmitter, a communication interface<sup>1</sup>) are input and can be used as needed. Coding is done in the block Onboard\_Matlab\_Control, shown in Fig. 20. This block can be modified as needed (or replaced completely) by the user's program. The block Attitude Control contains a similar control system to the ones discussed in the PID control section. The framework model can incorporate parameters that can be sent to the quadcopter and has many debugging channels and customizable options. Using Real Time Workshop (now called Simulink Coder), this model can be translated into C code. Using the Eclipse software and settings that came with the AscTec SDK, as well as the JTAG adapter (Joint Test Action Group, a programming interface hardware<sup>1</sup>), the code can be sent to the quadcopter and debugged.

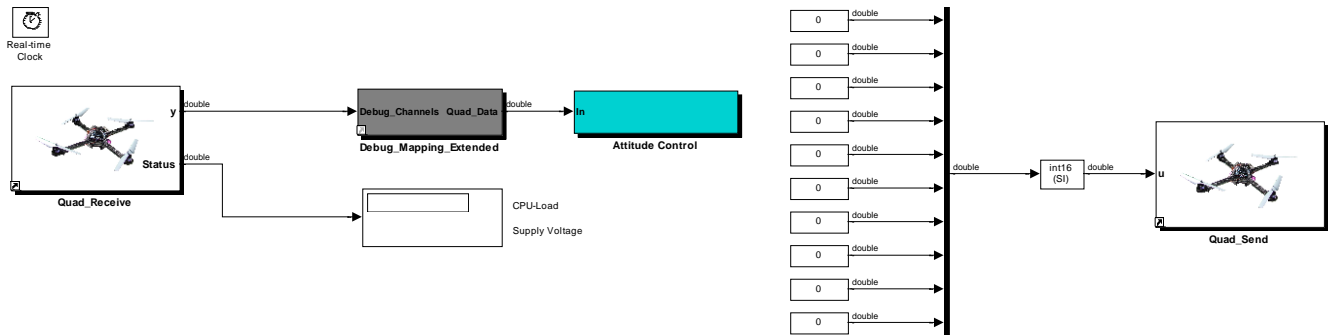


**Figure 20. Onboard\_Matlab\_Controller<sup>7</sup>.** This model shows the contents of the subsystem Onboard\_Matlab\_Controller from Fig. 19. This is where the user control program would go.



After initialization and transmission of parameters, the quadcopter is ready to fly. The quadcopter uses two wireless communication devices called Xbees. It can be used with one or two, but this system is set up with two, one for transmitting and one for receiving, enabling faster data transfer. The model in Fig. 21 shows the Simulink interface model that can send control channels and receive data from the quadcopter.

The blocks Quad\_Receive and Quad\_Send contain C code s-functions to interface with the Xbee hardware. The constant blocks connected to the Quad\_Send block are the commands sent to the quadcopter. Their function can be customized in the framework model. The data coming back from the quadcopter can also be partially customized in the framework. There are 60 debug channels to choose from, but only 20 channels are sent back to the computer at a time, with a rate of 50 Hz. The first block of ten is transmitted every cycle, including the IMU attitude and rotation, as well as the commanded values from the attitude control loop. The second block of ten is chosen from the remaining five blocks; it can be the same channels every time or it can loop through the blocks of channels as defined by the user. A signal was sent via a control channel and successfully received by a debug channel.

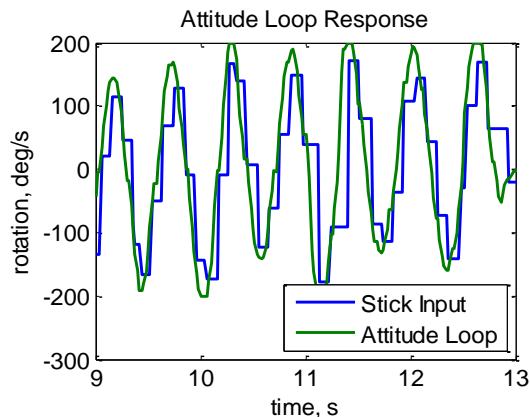


**Figure 21. Xbee-Quadrocopter Interface<sup>7</sup>.** This model uses the Xbees to interface with the quadcopter, sending commands and displaying the data.

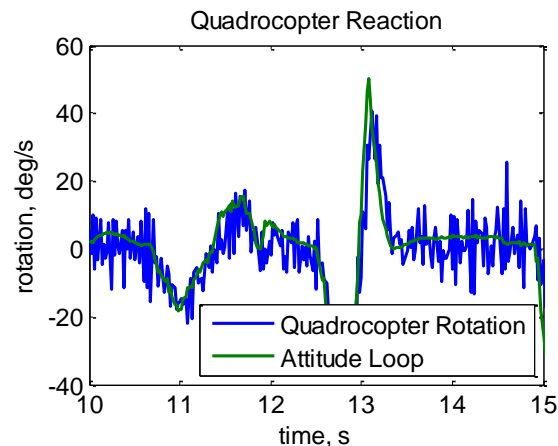
The setup in Fig. 21 displays the CPU load and battery voltage in the model. In the Attitude Control block, there are also scopes displaying the IMU data for attitude and rate, the commanded rates from the attitude control algorithm on the copter, the stick commands, and the resulting motor commands. This section was modified to output the data into Matlab for further analysis.

## B. Quadrocopter Data

When flying the quadcopter, the computer was set up to collect data, which was then analyzed in Matlab. In Fig. 22, the stick input and the response from the attitude loop are compared. Because the stick input is from -1 to 1 and has no real units, it was scaled to be displayed with the attitude loop data. The quadcopter was purposefully flown in such a manner as to produce the regular oscillations shown. Figure 23, from a different dataset, displays the reaction of the quadcopter to the given input. The data is from normal flight, so there is no pattern to it. The quadcopter rotation readings follow the attitude loop input with minor lag, but there is a lot of noise in the signal, whether it is from the sensor or the actual movement of the quadcopter.

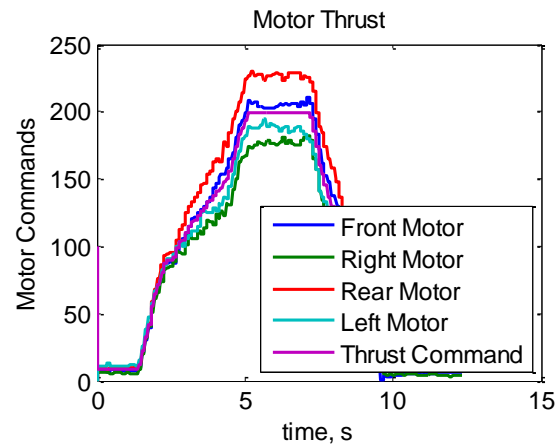


**Figure 22. Attitude Loop Response.** This figure compares the scaled input of the stick on the remote control to the commanded rate from the attitude loop.

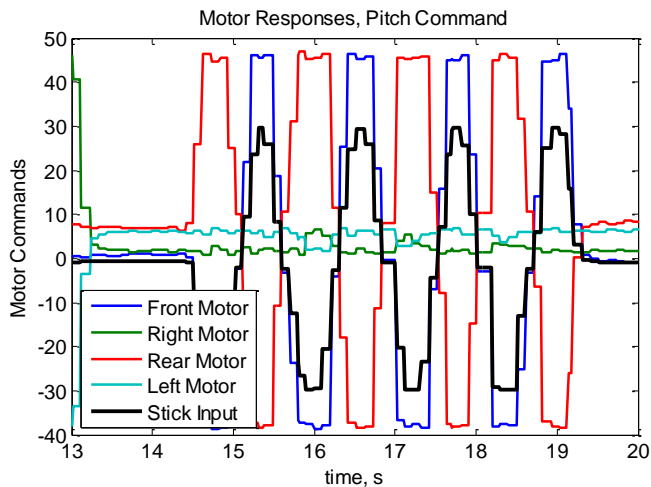


**Figure 23. Quadrocopter Reaction.** This figure compares the commanded rotation from the attitude loop with the IMU rotation data.

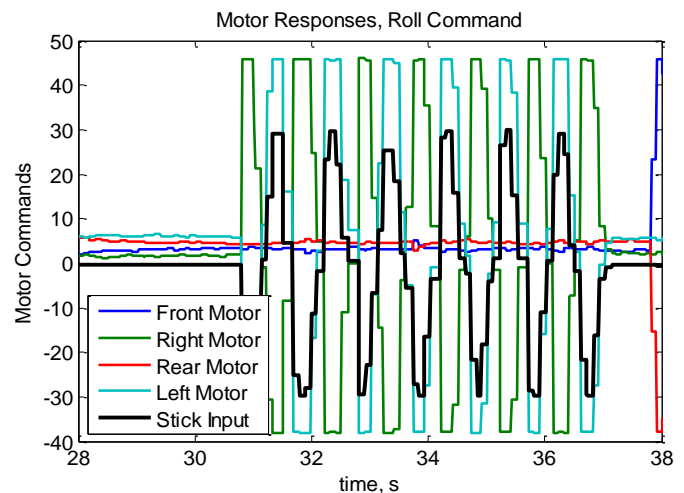
The data in Fig. 24 compares the commanded thrust value with the response of the motors. The thrust was taken up to maximum and then brought back down, during which the motors follow the signal with a varying degree of accuracy. When the thrust signal increased, the motor commands deviated, whereas at low thrust values, the motors followed the signal closely. As the thrust is scaled from -1 to 1 coming from the remote control and has no physical unit associated with it, it was scaled to the range of the motor commands. However, the motor commands are also of an arbitrary unit system, as that command is subsequently fed into the motor controllers on the quadcopter, which take the input and convert it to the appropriate RPM value for the motor.



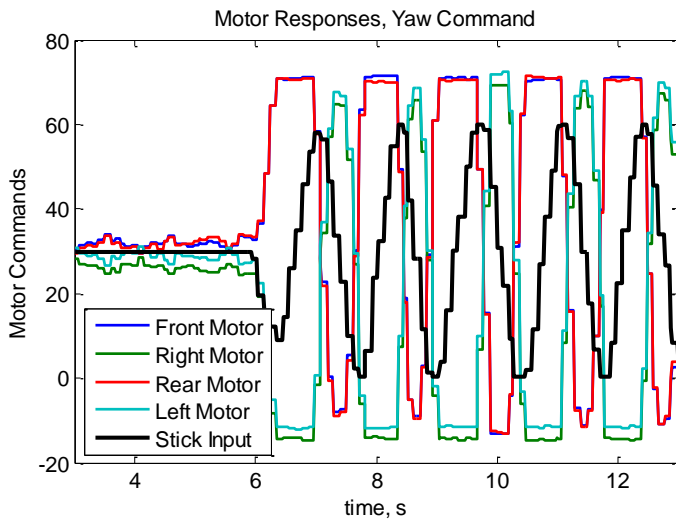
**Figure 24. Motor Thrust.** This figure compares the thrust command from the remote control with the resulting motor commands.



**Figure 25. Motor Response to Pitch Command.** By oscillating the pitch command, the correct motor responses were confirmed.



**Figure 26. Motor Response to Roll Command.** Confirmation of the correct motor responses to a roll command.



**Figure 27. Motor Response to Yaw Command.** As with the pitch and roll figures, the yaw command was oscillated, but as yaw has a different dynamic, all four motors engage as expected.

In Figs. 25, 26, and 27, the command signal for one axis was oscillated using the RC controller. The resulting motor responses were checked to confirm the response. For the pitch command (Fig. 25), only the front and rear motors are engaged, with the front having the opposite value of the rear. For the roll command (Fig. 26), the right and left motors are engaged. In Fig 27, all four motors are engaged to respond to the yaw command, as explained earlier. The clockwise spinning motors (front and rear) are paired, as are the counter-clockwise motors (left and right), and these pairs oscillate in an opposite manner. This axis has a noticeable lag, as opposed to the other two axes. As pitch and roll both only use two motors, the dynamics of these axes are similar. As is brought up in Ref 1, because the yaw axis is controlled by all four motors, it has different dynamics, causing the different response.

### C. Control Variations

The model in Fig. 19 is fully customizable, so steps were taken to make modify it in small increments. The first variation was to put a switch system in place so that one of the control channels in the model in Fig. 21 could be used to send a thrust command to the quadcopter instead of the RC controller. The second variation tried was to have the model output the height data from the IMU back to the computer so that it could be analyzed to estimate how high the quadcopter could fly when outside. Another variation was to adapt the PD controller model from the earlier control section back into the model in Fig. 19. This was the most successful variation, as the code was run on the quadcopter and parameters were sent to the quadcopter real-time. However, all of these variations, and other possibilities, are deserving of more time than could be afforded to them in this project. All of the variations mentioned were coded into C and run on the quadcopter, but none of the model variations performed quite as expected, and much care had to be taken not to disturb any of the important processes in the model when making changes.

### D. Camera Use

Some research and was done into mounting a camera on the quadcopter and learning to fly it through the first-person view. A small Bluetooth camera was attached on top of the quadcopter and a live video feed was received while flying. A Simulink diagram that overlays a heads-up display (HUD) onto the video feed from the quadcopter was also started, but figuring out how to plot data onto such a display proved to be a rather difficult task to complete in Simulink. Contacting Mathworks about this application produced some ideas, but there was no time to explore this further.

## V. Conclusion and Future Work

Through this project, the quadcopter system was successfully set up for future use, fulfilling the primary goal. By establishing a space to fly in and protocol for using the vehicle, others will be able to operate the quadcopter easily and safely. Documentation of the processes involved in flying, maintaining, and programming the quadcopter will make it easier for people to become involved in the project and keep the project running after this summer. Through learning to design a simple controller for the quadcopter, a model has been created for computer simulation of the quadcopter, and a PD controller was tested. Perhaps the biggest accomplishment of this project was the combination of hardware and software—using the AscTec SDK to program and edit code, and then load and test it on the quadcopter. Through receiving data back, the system was validated and debugged.

As the purpose of this project was to set up the quadcopter system for future use, this project has many future possibilities. A further step for testing GPS control would be to use the waypoint command feature. As for control design, a more optimal PD controller should be considered, making the best controller within the limitations of the gains. The controllers should also be verified for all axes and for values close to saturation. More advanced control algorithms and new control designs should be tested on this vehicle in the future, as that is the purpose for this quadcopter. Besides the control design, much more work can be done to customize the framework model and Xbee model for data input/output from the quadcopter. The onboard camera and HUD system also bears further development. One other promising option for using this quadcopter is navigation. There has been an idea about using a camera-equipped room to track the quadcopter for indoor navigation, and/or using an onboard camera for tracking and navigation. The testing of navigation sensors and algorithms may prove to be the most valuable use of the quadcopter. The goal is to get more people involved, and as that happens, more ideas will be brought to the quadcopter project. The project is open to exploration of ideas and improvements in control and navigation logic and is a cost-effective means of testing alternative control programs.

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